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APPLICATION OF MULTIVARIABLE CONTROL TO AIR VEHICLES

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Modern military aircraft make use of fly-by-wire flight control systems to enhance the pilot's ability to control the vehicle. Fly-by-wire systems were first developed in the 1960s and were used to alleviate the pilot's workload. Today, virtually all modern military aircraft use feedback control systems to modify the vehicle dynamics and to provide some level of autonomy

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Application of Multivariable Control to Air Vehicles

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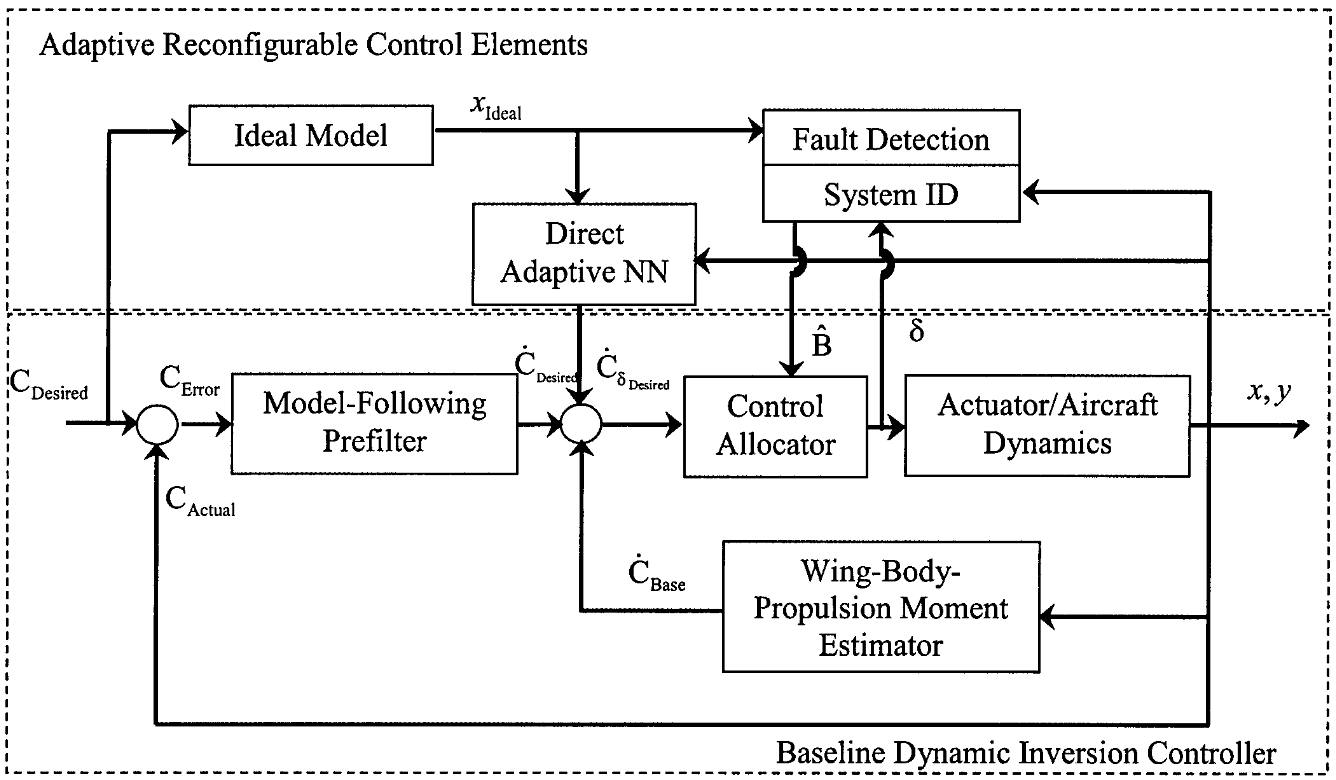
Modern military aircraft make use of fly-by-wire flight control systems to enhance the pilot's ability to control the vehicle. Fly-by wire systems were first developed in the 1960's and were used to alleviate the pilot's workload. Today, virtually all modern military aircraft use feedback control systems to modify the vehicle dynamics and to provide some level of autonomy.

The process of synthesizing flight control systems using classical single-loop methods, required that the aircraft dynamics be linearized at numerous points in the flight envelope. As a result of this requirement, the feedback gains had to be scheduled according to flight condition. Gain scheduling requires that large numbers of flight control gains be computed and stored in the aircraft flight computer. Multivariable flight control design methods have been evolving since the late 1960's that promised to alleviate some of the tuning inherent in the classical design process. Some of the more popular design techniques, such as those based on the Linear Quadratic Regulator and H-infinity, were optimization-based and were capable of handing multi-axis coupling. Unfortunately, these methods still required a linearized vehicle model as a starting point for the design and since they were optimization-based, they required considerable engineering judgment to decide exactly *what* should be optimized. It was generally agreed that the ultimate objective was to optimize the handling qualities of the closed-loop aircraft. What constitutes good handling qualities is largely subjective in nature and is not easily captured in a mathematical performance index. Furthermore, flight control designs based on these methods still required that numerous gain sets be computed for the flight conditions that an aircraft is expected to encounter. Nonetheless, one of the major contributions of multivariable control theory was that it provided designers with the ability to analyze the robustness of multi-loop control systems to parameter variations in the linearized models.

In the early 1990's a new control design methodology emerged called feedback linearization that was based on Isidori's seminal book. Dynamic Inversion is a special case of the general feedback linearization methodology that is particularly well suited to flight control applications. Dynamic Inversion is a control design technique that does not require a linearized model of the vehicle dynamics to begin the control synthesis process. Control systems designed using this technique can be written in terms of the nonlinear equations of motion for the vehicle. Stability and control information is also required to estimate the aerodynamic forces and moments at flight conditions that will be encountered by the vehicle. On aircraft, it is convenient to use this control methodology in conjunction with a model-following scheme. This is because aircraft with desirable handling qualities can be written in terms of simplified dynamic models. When Dynamic Inversion is used in a model-following framework, the open loop aircraft

dynamics are essentially replaced with the dynamics of a model that is known to have good flying qualities. The technique is used to provide the pilot with the ability to easily command a set of controlled variables. The body-axis angular rates are often chosen as the controlled variables, although they are sometimes blended with aerodynamic angles such as angle-of-attack and sideslip to avoid problems with unstable zero-dynamics. One of the major advantages of this type of control design is that it can use information from adaptive and reconfigurable control modules to provide tolerance to control effector failures or vehicle damage. The block diagram shown in Figure 1 will be helpful in understanding the interactions between the elements of a Dynamic Inversion-based adaptive/reconfigurable control system.



When Dynamic Inversion is applied to flight control synthesis, it is usually used to decouple and indeed cancel out, the rotational aircraft dynamics. These modified dynamics become a bank of decoupled integrators or a rate command system from the perspective of the vector of controlled variables **C**. The input to this modified controlled element is the command variable rate commands $\dot{\mathbf{C}}_{\text{Desired}}$, e.g. angular acceleration commands. The model following approach used to produce the desired command variable rates $\dot{\mathbf{C}}_{\text{Desired}}$, usually consists of a pre-filter that when combined with the modified controlled element, produces a closed-loop dynamic system that is known to have good flying qualities. Dynamic inversion control laws normally generate a small number of control variable rate commands that must be generated by the available control effector suite $\dot{\mathbf{C}}_{\delta_{\text{Desired}}}$. These pseudo-commands are often expressed in terms of the total

desired aerodynamic moment or angular acceleration. Normally, there are more control effectors than there are controlled variables or axes to control. This condition of control effector redundancy gives rise to the Control Allocation problem.

Control Allocation or control mixing can be used to generate any number of control effector commands δ from a small number of pseudo-commands $\dot{\mathbf{C}}_{\delta_{Desired}}$. In the simplest approaches, a control allocator does little more than gang control surfaces together to eliminate the condition of control redundancy that leads to an over-determined problem. Much more sophisticated Control Allocation algorithms have evolved over the past decade. Some of the most effective control allocators are based on constrained optimization methods that deliver the desired pseudo-commands while optimizing some sub-objective such as drag minimization or wing load alleviation. These algorithms generate commands that respect actuator rate and position limits. In other words, these control allocators generate actuator commands that deliver the desired control induced angular acceleration or moment, so long as it does not violate actuator rate or position limits. When it is not physically possible to deliver the desired moments or accelerations, the optimization-based approaches can minimize the difference between the actual and desired moments or accelerations. The control allocation problem arises quite naturally from the dynamic inversion formulation, but the algorithms may also be used to simplify the synthesis of classical or multivariable control systems that do not generate physically unrealizable actuator commands. Another enormous advantage of on-line control allocation is the ability to use direct or indirect control effector failure identification to update the information that the control allocator uses to generate actuator commands. Identification of failures or damage can be used to reconfigure the remaining control effectors in order to adapt to the failure. For example, if an elevon fails hard-over on an aircraft, the remaining elevon, ailerons and rudders may be used to balance the moments on the vehicle and allow the pilot to maintain control of the vehicle. The control allocator can even operate in a mode that takes advantage of a vehicle's control redundancy to enable indirect detection of failures or damage. In order to detect failures or damage using on-line system identification, the control surface deflections must be decorrelated and excited. Under nominal conditions, control allocators can make use of the control redundancy to achieve decorrelation and excitation without degrading the desired response of the vehicle.

The upper portion of Figure 1 contains a number of adaptive/reconfigurable control elements that can be used to augment the baseline Dynamic Inversion control law. The adaptive reconfigurable control elements can be incorporated as a module that enables the vehicle to recover nominal performance to the greatest extent possible when the vehicle is damaged or experiences control effector failures. An explicit model of the ideal closed loop vehicle is normally included so that deviations in the response of the actual vehicle can trigger fault detection logic that determines whether or not failures or damage has occurred. When a fault occurs, the on-line control allocator can change sub-objectives to decorrelate and excite the control effectors. This excitation must provide sufficient signal content to enable the on-line system identification algorithms to estimate the stability and control characteristics of the vehicle using a blend of apriori knowledge, sensor measurements and control surface deflections. The explicit model can also be used in

conjuction with a direct adaptive controller that modifies the pseudo command when differences between the ideal model and actual vehicle responses differ. The direct adaptive controller and indirect adaptive controller that relies on on-line system identification can work together to recover the nominal vehicle performance as closely as possible, given the physical limitations of the vehicle.

The Air Force Research Laboratory's Control Science Center of Excellence (COE) and its predecessors have been instrumental in the development of fly-by-wire flight control technology since the 1960's. Some of the more recent accomplishments made by the COE and its industry partners have been the flight demonstration of adaptive/reconfigurable control technology on the VISTA F-16 and the X-36 shown in Figures 2 and 3 respectively. A Self Designing Control System (SDC) was demonstrated on the variable stability VISTA F-16 aircraft in 1995. The SDC used on-line system identification to feed a receding horizon optimal control design method that modified flight control system gains in response to simulated effector failures. The SDC program resulted in the first-ever landing of a fighter, with an emulated missing horizontal tail under full reconfigurable control. The X-36 tailless fighter aircraft used a dynamic inversion control system with a control allocator as a baseline flight control system. Neural network based direct adaptive control was successfully used to augment this baseline flight control system. The objective of this direct adaptive method is to recover nominal flying qualities to the greatest extent possible in the presence of control effector failure or vehicle damage. The system was successfully flight demonstrated and underwent extensive hardware in the loop ground-testing. The adaptive flight control systems were found to dramatically improve the flying qualities of the vehicles in the presence of failures or damage. The success of the VISTA and X-36 flight tests have resulted in increased confidence in adaptive/reconfigurable control technology. As a result, some of this technology is now being transitioned to munitions platforms such as the Joint Direct Attack Munition System (JDAMS) and the Block-2 flight control system of the Boeing X-45 Unmanned Combat Air Vehicle (UCAV) shown in Figure 4. In the case of JDAMS, the direct adaptive control technology has transitioned from the COE to AFRL's munitions directorate that is using the technique to reduce modeling requirements associated with converting unguided munitions into smart weapons using the JDAMS tail-kit.

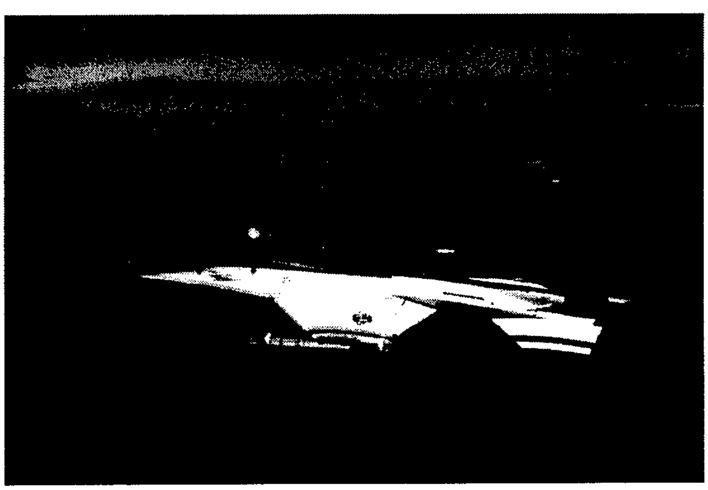


Figure 2. VISTA F-16 Variable Stability Aircraft

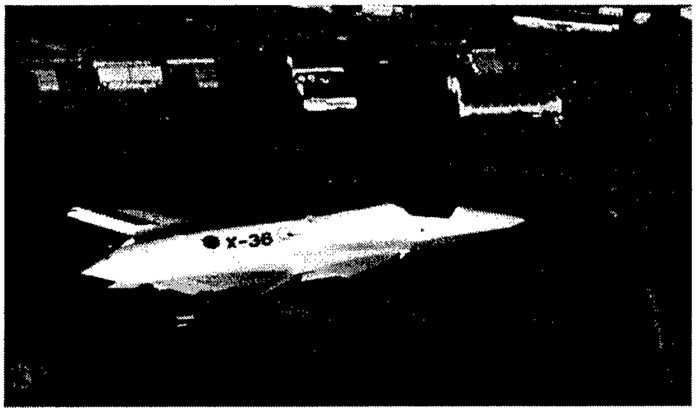


Figure 3. Boeing X-36 Tailless Fight Aircraft

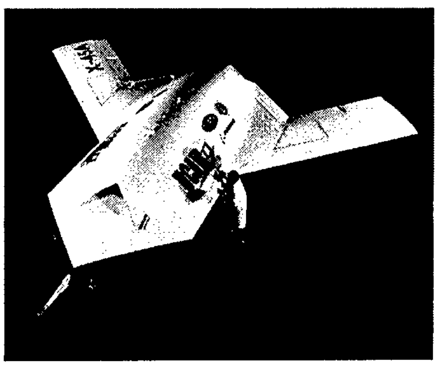


Figure 4. Boeing Unmanned Combat Air Vehicle (UCAV)

Prototypes of Joint Strike Fighter (JSF) have used dynamic inversion and control allocation technology to produce a fighter plane with excellent handling qualities. The COE now working to transition the control technologies developed for fighter aircraft to tomorrow's reusable space-access vehicles. Recent work has focused on developing full-envelope, trajectory independent flight control systems for reusable launch vehicles. The COE also participated in NASA Marshall Space Flight Center's advanced guidance and control project for the X-33 where it developed highly promising adaptive/reconfigurable flight control system for the ascent flight phase. Current research is focusing on the development of integrated adaptive guidance and control for autonomous space-access vehicles. It has been found that even with adaptive/reconfigurable control, the closed-inner-loop performance of autonomous aircraft can degrade in the presence of vehicle failures or damage. Since there is no pilot onboard to adjust the reference trajectory and guidance commands, autonomous system must perform these tasks online. The COE and its industry partners are now preparing to flight demonstrate a promising integrated adaptive guidance and control (IAG&C) algorithm using the VISTA F-16 to simulate the X-40A Space Maneuvering Vehicle shown in Figure 5. The X-40A is an 80% scale version of the X-37 that has been used to flight demonstrate an autonomous landing system for reentry vehicles. The successful

demonstration of IAG&C technology on the VISTA F-16 may lead to actual X-40A drop-test demonstrations of the technology in the next few years.

Figure 5. X-40A Space Manuevering Vehicle.